Vortex-type domain structure in Co-rich amorphous wires

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Investigation of the surface magnetic domain structure has been performed in Co-rich, nearly zero magnetostrictive, amorphous wires using magneto-optical Kerr effect magnetometry and microscopy. The formation and motion of a multidomain vortex-type structure with curved domain walls have been observed in amorphous wires. The possible origins of the existence of the vortex-type structures in these amorphous wires are discussed. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1646439]

The magnetic properties of amorphous wire prepared by an in-rotating-water quenching technique are very interesting because of their potential technological applications. Co-rich wires with nearly zero magnetostriction attract special attention, because they show a giant magnetoimpedance (GMI) effect[1,2] that has recently been found in these wires. This GMI effect is of great interest in sensor applications. The importance of investigating the magnetic structures in the surface area of the wires is demonstrated by the known correlation between the GMI and the magnetic skin effect. The present work is devoted to the investigation of magnetic domain structure in the outer shell of an amorphous wire because of its special place in the origin of the GMI effect.[3] As it was noted in Ref. 4, the impedance is sensitive to a surface magnetic configuration at high frequencies when the skin effect is essential; therefore, the characteristic features of impedance-field behavior are closely related to a quasistatic magnetization process. During the experiments, special attention was given to the behavior of the surface domains under the action of an axial magnetic field, considering that the GMI effect is very sensitive to the axial magnetic field. It was also taken into account that the transformation of surface magnetic domain structure under axial magnetic field has not been studied in detail in these wires. The investigations have been performed using the magneto-optic Kerr effect (MOKE) technique, which is recommended as a very useful and informative method for the study of the surface domain structure in amorphous ferromagnetic wires.[5,6]

The investigations have been performed in nearly zero magnetostrictive, amorphous wire having circumferential magnetic anisotropy in the outer shell. The Co-rich ferromagnetic wires of nominal composition $(Co_{94}Fe_6)_{72.5}Si_{12.5}B_{15}$ (diameter 120 μm) obtained by an in-rotating-water quenching technique were produced by Unitika Ltd. The length of the studied wires was 7 cm. The process of magnetization reversal in the surface area of the wires has been studied by a MOKE loop tracer and by a Kerr microscope employing an image processor. When the loop tracer was used, a polarized light of He-Ne laser was reflected from the wire to the detector. The beam diameter was 0.8 mm. For the case of the transverse Kerr effect, the intensity of the reflected light was proportional to the magnetization, which was perpendicular to the plane of the light. For the case of the longitudinal Kerr effect, the rotation of the angle of the light polarization was proportional to the magnetization, which was parallel to the plane of the light. A pair of Helmholtz coils provided an axial magnetic field. To produce the circular magnetic field, an electric current flowing through the wire has been used.

Figure 1 presents the transverse Kerr effect dependence on the electric current (I) flowing through the wire and producing the circular magnetic field. In addition, Fig. 1 presents the domain patterns obtained by the Kerr microscope. The magnetization reversal appears between two states with opposite directions of circular magnetization in the outer shell of the wire. The "black" and "white" colors correspond to these two opposite directions of the circular magnetization. It is possible to observe the nucleation of circular domains with successive domain-wall (DW) propagation [Fig. 1(b)] and the formation of the domain structure of bamboo type [Fig. 1(c)]. The change of the DW shape takes place during the DW propagation. This is related to pining effect of the DWs.

If the behavior of surface magnetic structure in the circular magnetic field looks as is predicted taking into account the circular anisotropy in the outer shell, the results of magneto-optical experiments for the case of axial magnetic

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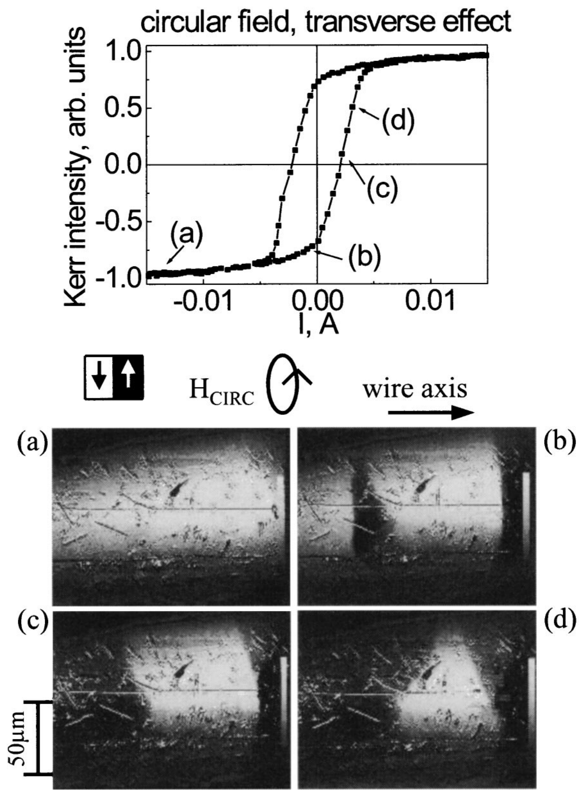

FIG. 1. Transverse Kerr effect hysteresis loop obtained in circular magnetic field and images of surface domain structure.

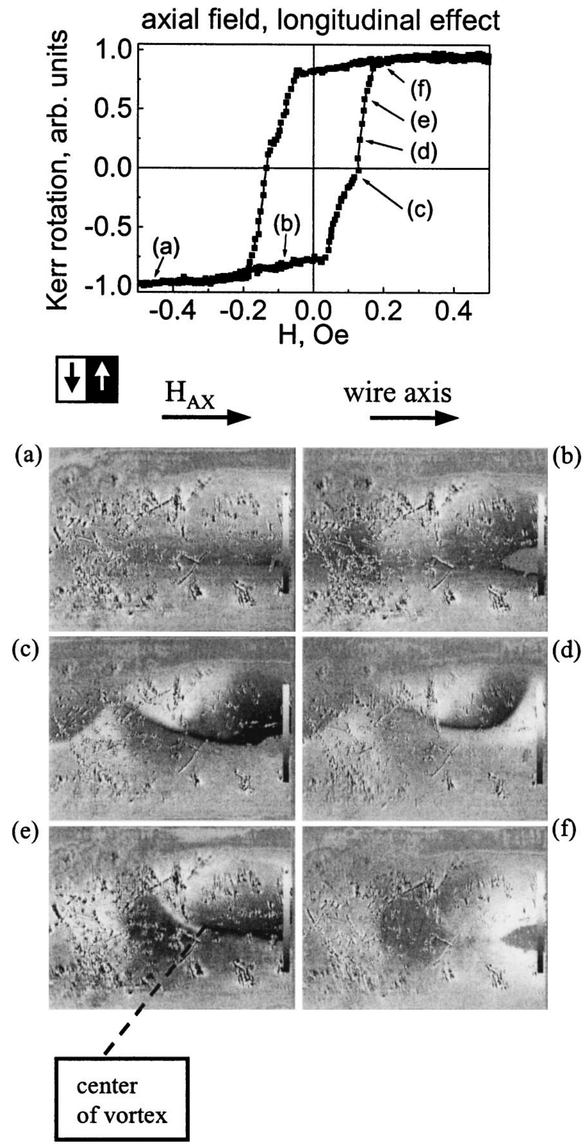

FIG. 2. Longitudinal Kerr effect hysteresis loop obtained in axial magnetic field and images of surface domain structure.

field are unexpected. Figure 2 presents the hysteresis loop and the domain patterns obtained when the external magnetic field was applied along the wire axis, that is, perpendicular to the direction of circular surface anisotropy. At the first stage of the magnetization reversal process [Fig. 2(b)], the change of magneto-optical contrast, observed in some areas, can be attributed to the rotation of the magnetization. Further, the complex multidomain structure appeas [Fig. 2(c)]. The transformation of this domain structure is accompanied by the DW motion [Figs. 2(d) and 2(e)]. At the last stage of the magnetization reversal process, fluent change of the contrast also takes place [Fig. 2(f)].

Analyzing the results obtained, we used the schematic pictures of domain structure in the outer shell of the wire (Fig. 3). When the absolute value of the axial magnetic field is high, the magnetization is directed along the wire axis [Figs. 3(a) and 3(f)]. These conditions are depicted as ''gray'' [Fig. 2(a)]. When the magnetic field decreases, the change of the contrast occurs in the wire surface and the formation of some modulated structure is observed [Fig. 2(b)]. The axial projection of the magnetization in these predomain states is equal, but the circular projections differ from each other [Fig. 3(b)]. The appearance of domains with the opposite axial direction of the magnetization [Fig. 2(c)] is the second stage of the magnetization reversal. This moment is shown schematically in the Fig. 3(c). This appearance is reflected in the hysteresis loop (Fig. 2) as a sharp change of the magneto-optical signal. Thus, domains of four types exist on this stage. They are marked as 1, 2, 3, and 4. The DWs between the domains of 1-3 and 2-4 types are clearly observed, but the positions of DWs between the domains of 1-2 and 3-4 are not so evident. It should be related to the value of the angle Φ at which the magnetization rotates in the DWs. There are two types of DWs. The angle Φ of the DWs of the first type is close to 180° and is easily observed. The angle Φ of the DWs of the second type is small and is determined by the inclination of the magnetization from the axial direction. During the magnetization reversal, fluent DW motion and jump-like rearrangement of the whole domain structure takes place. In this way, the domains of 3-4 types replace the domains of 1-2 types [Figs. 2(e) and 2(f)]. Further, the magnetization in the domains of 3-4 types rotates towards the axial direction and the contrast disappears.

The four-domain structure presented in the Figs. 2(c)–2(e) can be considered as a specific magnetic vortex.[7] Rotation of the magnetization by 360° appears in this vortex. Under the action of an axial magnetic field, the vortex moves compactly in the surface of the wire, taking part in this way in the magnetization reversal. In the Fig. 2(e) the domain

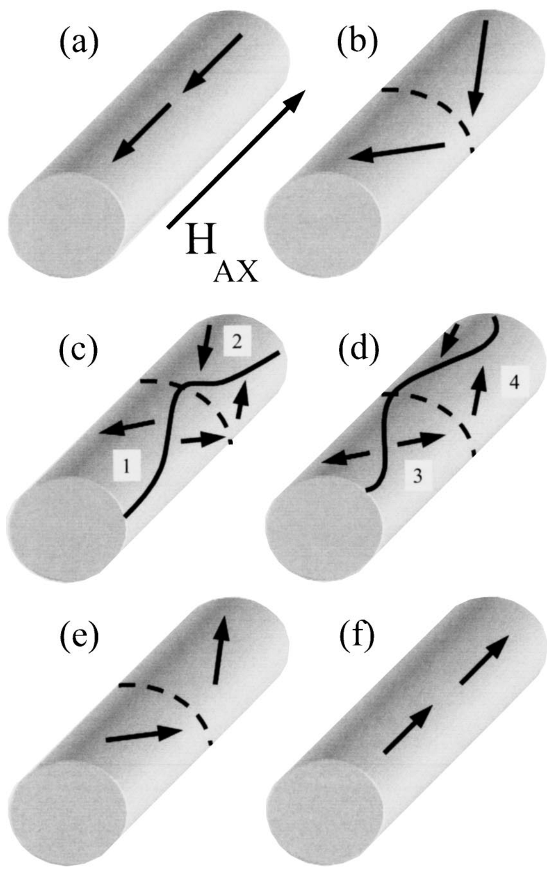

FIG. 3. Schematic diagram of the evolution of the surface domain structure in the axial magnetic field. Arrows show directions of the magnetization in the surface domain structure.

structure is presented, at which the ''center'' of vortex is demonstrated. It is a point at which the ''black'' DW is changed by the ''white'' one. The formation of this structure could be considered as the result of the relations among the surface circular anisotropy, external axial magnetic field, and DW mobility. It is possible to suppose two limiting factors of magnetization reversal. The first one is only the rotation of magnetization, when the mobility of DW is low enough (the pinning is high enough). The second one is the nucleation of the domains with the magnetization axially directed and the successive DW motion. This is possible when the circular anisotropy is low and the DW mobility is high. In the present experiments, we can observe some intermediate regime in which the rotation of the magnetization is changed at some moment by the domain nucleation and the DW motion. The vortex structure appears at this moment.

One of the additional reasons for the vortex structure appearance could be the shape anisotropy of the wire. As was shown in Ref. 8, the nonplanar nature of the sample could initiate the formation of magnetization fluctuation of the vortex type. From another perspective, in Ref. 9, it was demonstrated theoretically that the formation of some twisted structure in the inner core of Co-rich amorphous wires is possible. Thus, the experimentally observed vortex-type structure could be considered as a reflection of the domain structure rearrangement in the inner core in the context of a strong relation between domain structure in the inner core and the outer shell of the wire.

In conclusion, the mechanism of the magnetization reversal process has been investigated in Co-rich, nearly zero magnetostrictive, amorphous wires with circular surface anisotropy using MOKE. It was found that in the presence of an axial magnetic field, magnetization reversal appears as a fluent rotation of the magnetization, followed by the formation of a domain structure containing domains of four different types, and curved domain walls. This structure, which can move along the wire surface, could be considered as a magnetic vortex. The formation of the vortex-type structure in the surface of the wire could be related to some twisting process appearing in the inner core of the wire and to the cylindrical-shaped anisotropy.

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